Geoacoustic and Tomographic Inversion of Haro Strait Data

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LONG TERM GOALS

The primary long term objective of this project remains:

- to provide a real-time, area-wide technique in shallow water for the estimation of volumetric (3-D) geoacoustic parameters.

These parameters are vital inputs for SONAR models (and subsequent signal processing and target localization methods) and include: *geometric values* (such as source location, array element location, and water depths) as well as *bottom properties* (such as sediment layer thicknesses, sound-speed profiles, densities, and attenuations). This area- wide estimation would be made via multiple air-deployed receiver arrays and multiple broadband air-deployed low frequency sources.

OBJECTIVES

The objectives of this second year's work included:

- Investigation of array configurations (phone depths and ranges). No sensors were applied to Haro Strait arrays to give information on phone locations. Thus, what happens when unknown *array parameters* are simply *added* to the overall parameter search space?

- Broadband (BB) inversion using MFP (with 4 frequencies all of which must have Bartlett values > 0.90 at each frequency). Will 4 frequencies be sufficient to allow GI convergence to a "solution", even for simulated "data"?

- Consideration of concurrent multiple sources for GI. What can we gain by the consideration of more than one source for an inversion?

- Demonstration of a full tomographic inversion of Haro St. data.

APPROACH

The work of last year by Tolstoy ('06a,b) examined time domain reflection arrivals (the first four: surface reflected, bottom reflected, surface-bottom reflected, and bottom-surface reflected) where the environment was range-dependent (RD) with a linear bottom slope. We found that data for a short range source-to-receiver (SR) path (to the NW array from source 14, range approximately 200m to 300m) showed very good separation between reflection arrivals (except on rare occasions when arrivals overlap) and had very good signal-to-noise (S/N, a strong signal). Arrival separations and good

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S/N were necessary for our geometric inversions. Using simple geometric relationships we were able to find geometric values to match the observed NW014 data with time domain predictions made by a RD BB model[1]. However, *many thousands* of data fits were possible, i.e., there were thousands of source ranges, phone depths, water depths, etc., which gave *identical* time domain arrival structures.

Thus, we conclude that using only time domain arrivals may result in "data fits" rather than "solutions" where:

- a solution is defined as a *unique* fit from any perspective. That is, a solution must fit the time domain data and all individual frequencies (from FFTs if necessary) as well as any array subsets of data. A "solution" is predictive while a "data fit" may not be.

Clearly, all solutions are data fits but not all data fits are solutions (Tolstoy, '08a).

Having devised a method to compute *all possible geometries* which will fit the time domain data, we have reduced the possible parameter intervals somewhat -- but not enough to find a "solution" to any Haro Strait path. In Fig. 1 (upper left) we see the possible locations (ranges and depths) for the top phone of the NW array during shot 14 based on the geometry alone (there are also comparable figures for source depth, water depth at the source, and water depth at the array). Thus, the top phone at (rge1,zph1) must lie in the range interval [225,380]m (Δr = 155m), depth interval [54,84]m (Δz = 30m). This is still quite a large search space for phone 1. Can we reduce these intervals?

Consider all the possible ranges and depths for phone 4 (again matching the time domain data). If we now require that this phone be within 19m distance of phone 1 and that both have the same source depth and water depth at the source, then we see a reduced set of possibilities for phone 1 as seen in the black circles of Fig. 1, upper right. If we restrict possibilities similarly using phone 7 as well, we have the black circles of Fig. 1, lower left, while finally requiring fits and restrictions to phone 15 as well (4 phones total) we arrive at the black circles of Fig. 1, lower right. Clearly, we have reduced the search space substantially (now the range interval is [235,295]m (Δr = 60m), depth interval is [55,67]m (Δz = 12m)). Unfortunately, even these smaller intervals are not small enough for an exhaustive search including other parameters. Allowing for phone 1 range samples every 5m, depth samples every 2m, we would require 91 tests for every source depth (10?), water depth at the source (10?), water depth at the array (10?), possible sediment surface sound-speeds (5?), and at each frequency of interest. This could easily lead to a few hundred thousand tests assuming a simple vertical line array (VLA) for 4 phones using a RD model[2]. What happens to the Bartlett MFP value for these possible test values (we will consider "high" frequencies (in the neighborhood of 500Hz) so that only the surficial sediment properties will be significant as in Tolstoy, '98, '04, '08b)? Can we just look for a single large value?

First, consider simulated data. In particular, consider the BB (200 to 800Hz) fields corresponding to those used by the RAMGEO model to match the time domain data of NW014 (as in Tolstoy, '06b) where the "true" source range is 248m and where the field is recorded on a VLA with the top phone at 58m. For the inversions we will include the top phone depth as an unknown. If we plot the *number* of possible source ranges versus source range using the time domain geometry only (using the top 4 phones as in Fig. 1 lower right which also used 4 phones but not consecutive ones) we arrive at the

[1] Predictions are made by the RD BB model RAMGEO, see Collins, '94, and Jensen et al., '94.
[2] We note that 360,000 tests at 10 tests per second requires about 10hrs of CPU.

black circles of Fig. 2 (the "true" value is indicated by the vertical solid line). The interval of possible source ranges is [220,290]m (Δr = 70m, an interval similar to that seen in the data of Fig. 1). If we examine the 490Hz component (several hundred thousand test cases), and require that the Bartlett MFP value must be 0.9 or greater, then we arrive at the blue triangles of Fig. 2. The interval of possible source ranges for large values of MFP is now [235,275]m (Δr = 40m). While the search interval for possible source range has been reduced, it is not down to a single range -- we see a lot of situations for which the time domain "data" has been fit as well as for which MFP > 0.90. What about considering more frequencies?

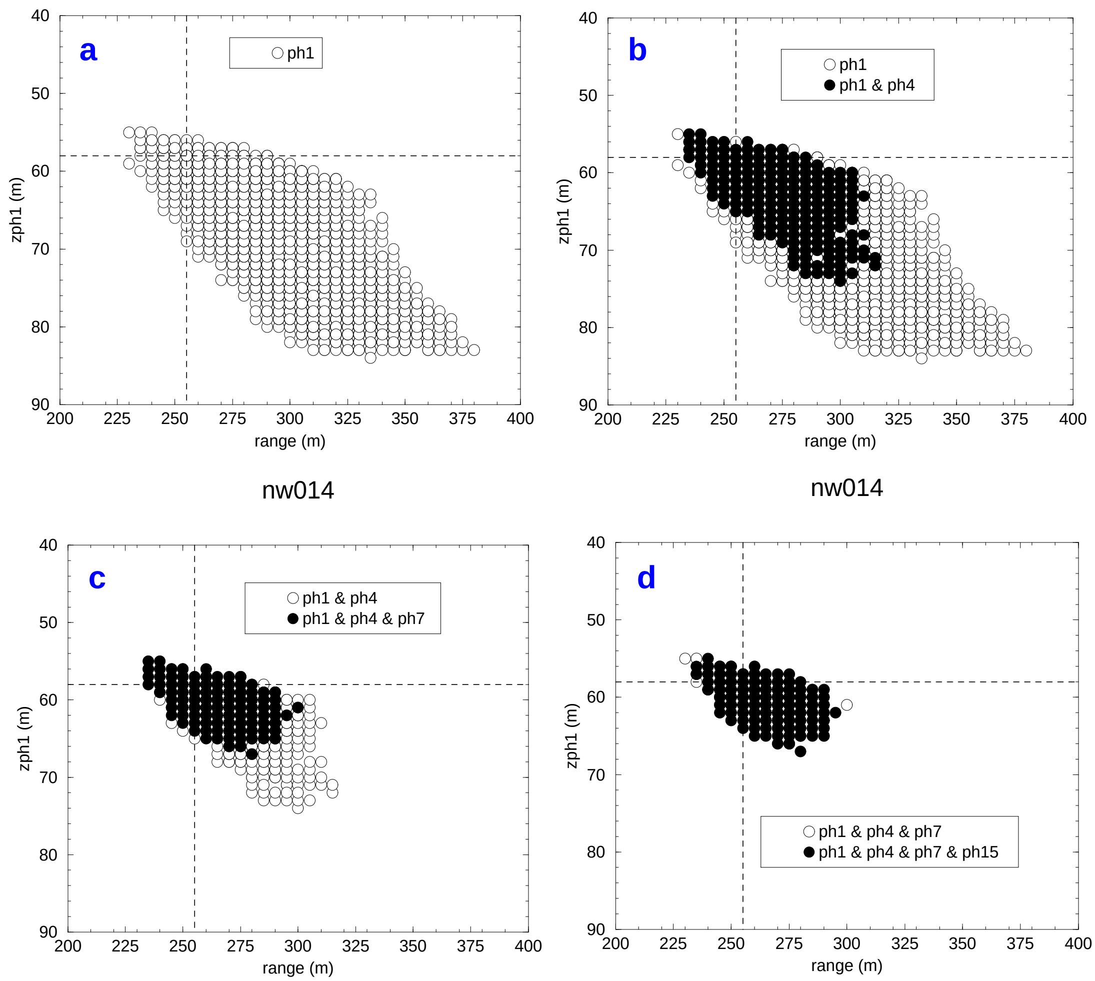


Figure 1. Plots showing possible ranges and depths to fit the time domain data for the top phone of the NW014. For (a) we see unrestricted possibilities (nearly 3000) for phone 1 alone. For (b) we also consider only those values for phone 1 which are also within an appropriate distance of phone 4 and which have common source depth and water depth at that source (black circles). For (c) we have the possibilities of (b) above and require that phone 7 be within an appropriate distance of phone 4 plus common source depth and water depth at that source (black circles). For (d) we have the possibilities of (c) above and require that phone 15 be within an appropriate distance of phone 7 plus common source depth and water depth at that source (black circles). For the last set we see the reduced possibilities for phone 1 locations assuming an acceptable array of four phones (with distance constraints), but the **array** ***can have hundreds of thousands of shapes.***

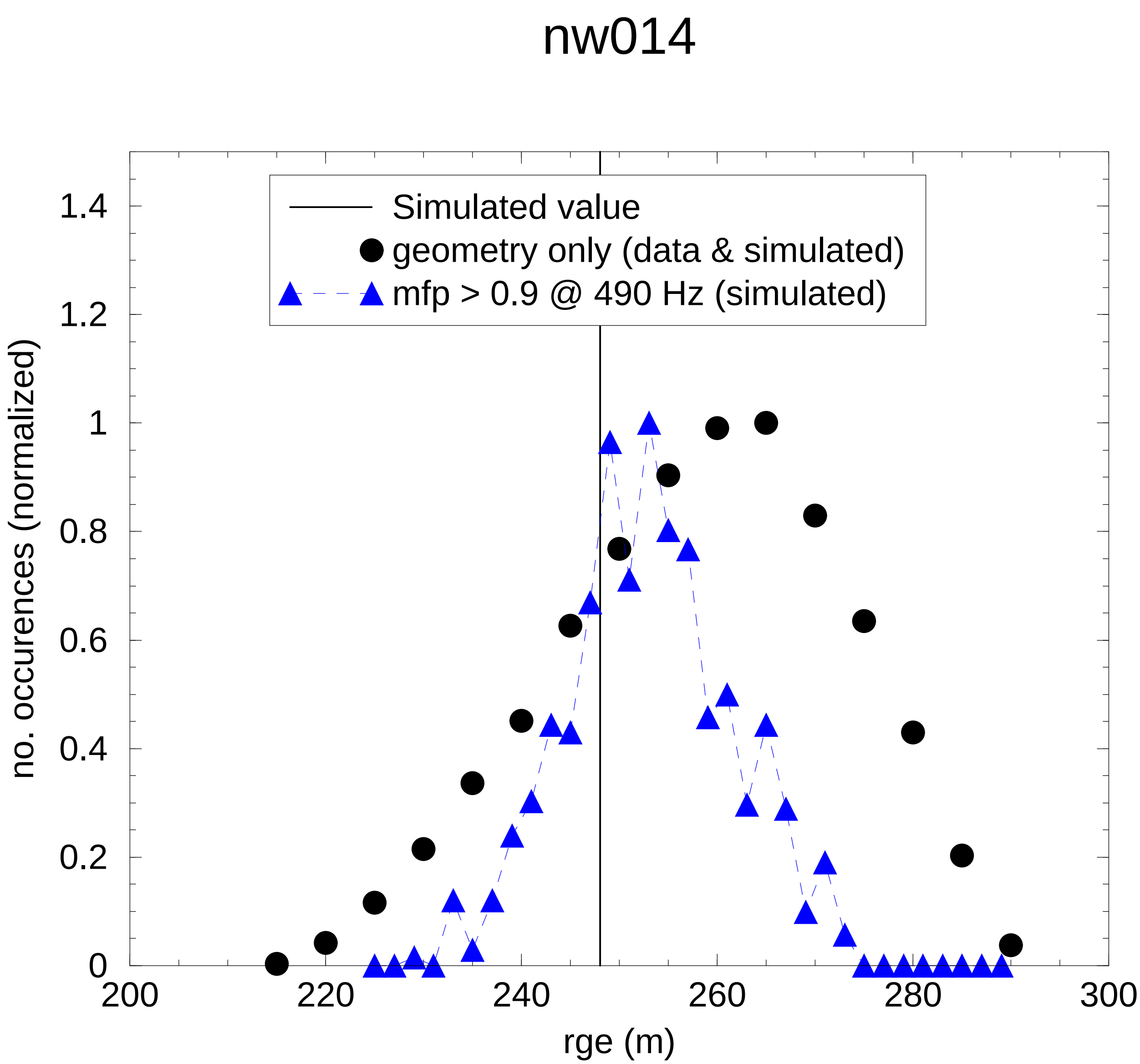


Figure 2. In this figure for the simulated "data" we see candidate source locations (ranges and depths based on geometric restrictions) indicated by the filled circles while the blue triangles show where the mfp correlations (comparison of "data" and PE simulations at 490 Hz)are greater than 0.9. We see numerous possible array depths (55, 56, 57, 58, 59 m), numerous possible water depths, and numerous possible source locations (ranges and depths) which have excellent mfp correlation values. The "true" source range is indicated by the vertical line at rge = 248 m. We clearly see that for this single frequency (490 Hz) we cannot expect to uniquely determine the geometric or geoacoustic properties for nw014.

Continuing in this fashion, we examine 3 other nearby frequencies (489Hz, 496Hz, and 497Hz) demanding that all 4 frequencies have Bartlett values > 0.90 to arrive at a final source range interval of [240,255] (Δr = 15m) with a maximum number of high (> 0.90) MFP Bartlett values at 246m. The largest MFP values (1.00) occur at 246m and 248m suggesting that *in the absence of noise*, BB MFP

plus the geometric inversion with array restraints may go a long way toward finding a "solution". However, what happens for *data* where noise will confuse the results?

Returning to the NW014 data (assuming a simple VLA for the top 4 phones alone), we find that while it is possible to find many situations for which the MFP values are > 0.90 at a single frequency (some values are as high as 0.96), we can *not* find a scenario for which *four* frequencies are simultaneously > 0.90. If we simply average the values, we find an overall maximum MFP of only 0.85 for all 4 frequencies with one scenario. How about using another nearby source to improve array configuration estimates, i.e., consider non VLAs but still reduce the number of possible test cases to a manageable number?

Consider the nearby (physically and temporally) shot 15 data, and let us require that for both sources 14 and 15 we must have:

- phone depths the same,
- water depths at the phones the same,
- appropriate distances between phones,
- no array snaking,
- no extreme array tilts (less than 30 degrees).

Then, we find a number of possible arrays for which MFP values are high (at a single frequency). However, the only arrays common to both sources must be *3-D*. That is, the array must tilt out of the plane for each source, leaning toward one source but away from the other. This kind of situation is illustrated in Fig. 3. Investigations for multiple frequencies with these 3-D arrays still need to be investigated.

We find that GI for the NW014 path has been unsuccessful so far at finding a "solution". Many data fits to the time domain data can be found, many high value MFP scenarios using a 4 phone VLA can be found at one, two, and even three frequencies, but not at *four* frequencies. Use of a nearby second source suggests that the array may not be vertical, even for just the top four phones but may be 3-D. Consideration of 3-D arrays at 4 frequencies demands an enormous amount of CPU time to thoroughly search possible scenarios, and this has not yet been successful. If we had phone sensors and *knew* the phone depths and their relative ranges, we could reduce the initial source range search interval significantly, thereby reducing CPU times as well. We do not have this information. However, what about the tomographic results which need these individual SR inversions?

We would like to perform the tomographic inversion on this data set. This is a very potent method -- when it can be applied. Advantages of the MFP tomographic method include:

- no initial estimates of parameters are needed;
- it is independent of the unknown parameter (water depth, bottom sound-speeds, densities, attenuations, etc.);

- it is independent of the number of parameters per grid cell;
- it is independent of the inter-relationships between parameters (such as range versus water depth);
- it is extremely fast (after individual path inversions have been performed);
- more resources (more sources, more arrays) result in improved inversion resolution.

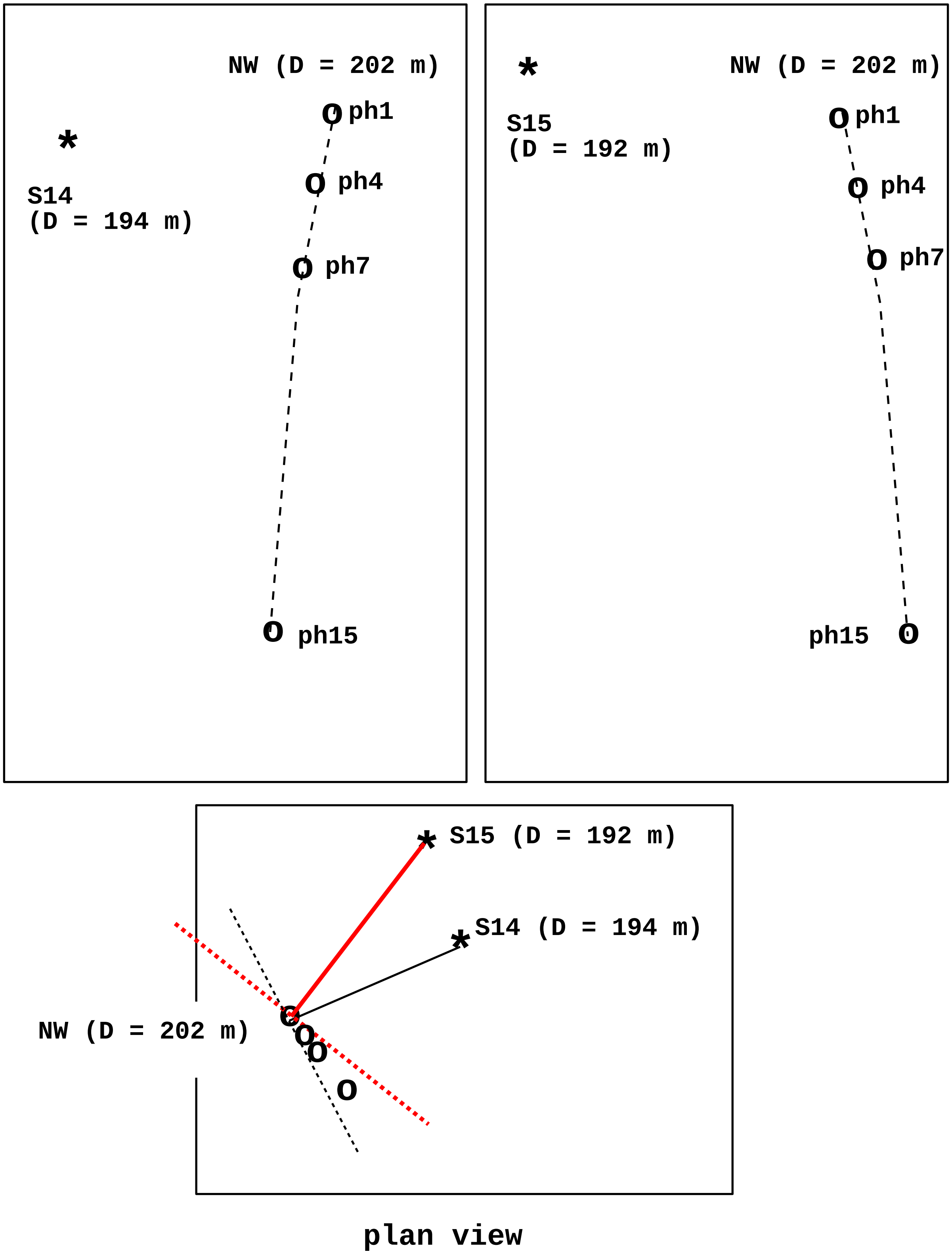


Figure 3. A sample 3-D array for 2 nearby sources (NW014 and NW015). Water depths are indicated by D values.

Disadvantages to the method include:

- multiple receiving arrays (preferably vertical) are required;

- multiple low (100Hz – 500Hz) multi-frequency sources are required;

- preliminary SR path inversions are necessary to estimate average parameters and must be high quality;

- parameters at the source and array locations must be known or pre-determined, e.g., by path inversions.

Even though we were unsuccessful at some of the individual SR inversions, we can still perform the Haro Strait tomographic inversion via simulation to estimate water depth results as though the preliminary SR inversions had been successful, i.e., as if we had obtained values per SR path for depths at the sources and arrays, and for average depth values per SR path.

The procedure first requires that we grid the region into cells, e.g., 100m x 100m (300 cells) as shown in Fig. 4 where the top subplot shows the "true" water depths of the region (each cell is assumed to have a constant water depth), the middle subplot shows the gridding and the source-array locations, the bottom subplot shows the 148 cells to be determined (light green). We note that cells with no acoustic sampling are not considered -- there are 120 of them here (dark blue), and 32 cells have sources and/or arrays contained within them (red, for which depth values are "known" by previous inversions, if this were possible).

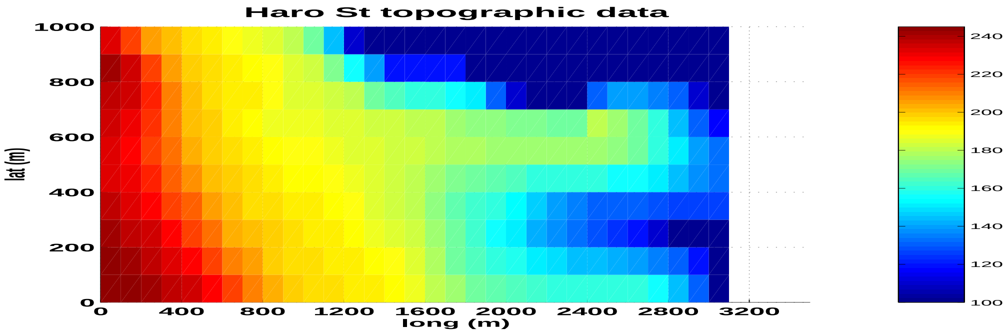
Unfortunately, the matrix associated with this gridding has a very poor, i.e., large, condition number Λ. This means that the tomographic inversion would not be good. If we reduce the number of cells to be inverted for by eliminating those with only a few acoustic paths (these cells do not have very good acoustic sampling), then Λ has improved but not a lot. Since we cannot change the distribution of the sources, the number of sources, or the number of arrays, we must re-grid the region to improve the number of paths per cell. If we now consider cells that are 200m x 200m (resulting in 75 cells total, 26 to be solved for) then Λ is now much more reasonable. Then, the tomographic inversion gives decent results but an rms error of 31.5m and a maximum error of 104.7m. If we eliminate those cells with fewer than 5 paths, then we are left with 23 cells to invert (nearly the same number) but Λ is even better, and we now show an rms error of 13.4m, a maximum error of 41.3m, with the results of the inversion shown in Fig. 5 (the top subplot shows the "true" water depths while the bottom subplot shows the inversion results). It should be noted that regularization of this inversion as suggested by Dosso (and discussed in Dosso et al., '98) may help considerably to improve results. Regularization would allow *a priori* information (such as values at the sources and arrays) to be more influential and would allow neighboring values to directly impact on results. Thus, abrupt transitions in values between cells would be minimized. Regularization might also produce fine scale results even from crude gridding.

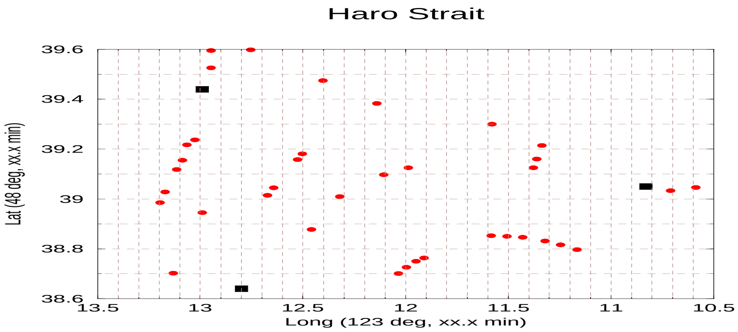
WORK COMPLETED

Recent work (FY07) completed includes:

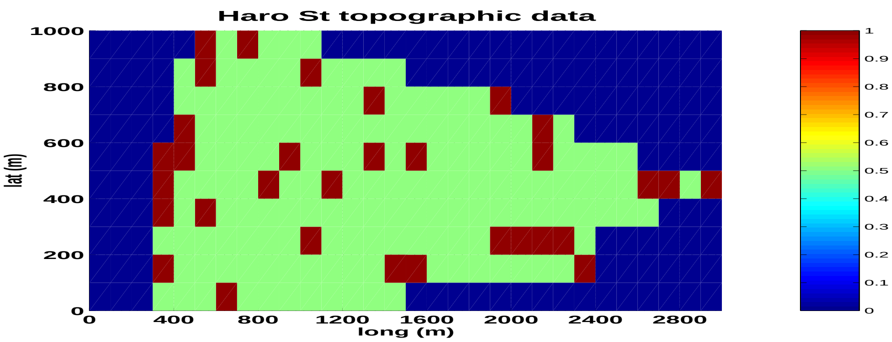
- Investigation of array configurations.
- Broadband (BB) inversion using MFP.
- Consideration of concurrent multiple sources for GI.
- Demonstration of a full tomographic inversion of Haro St. water depths.

True values





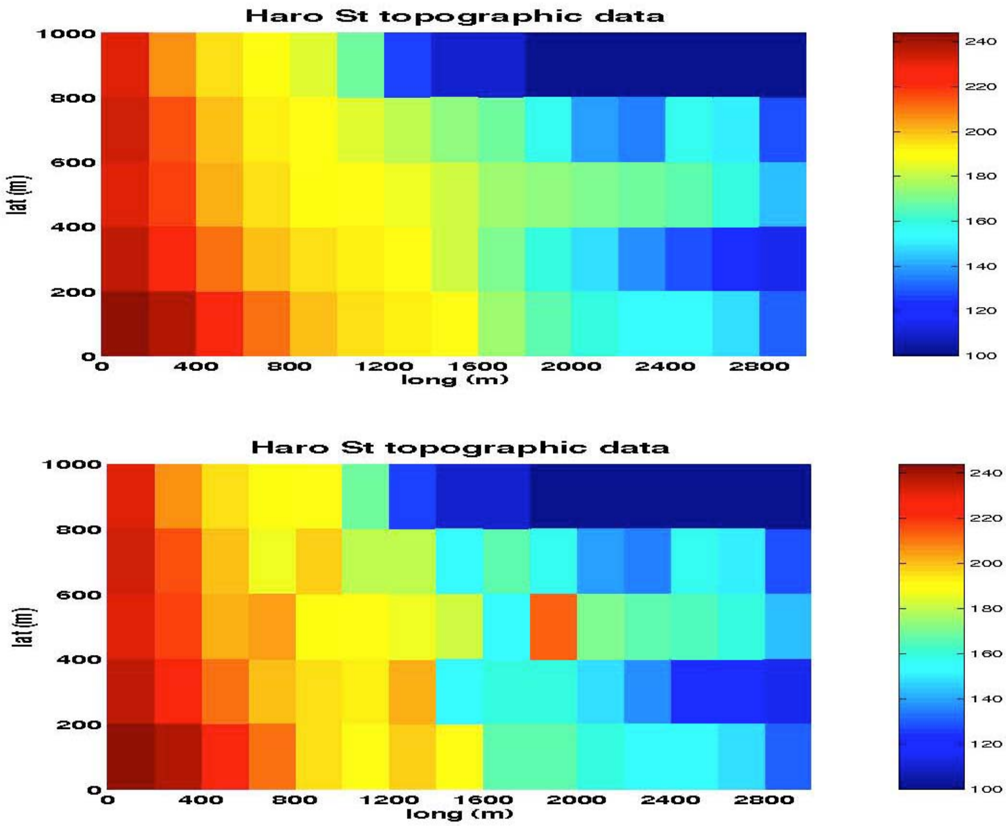
Source and array distribution



Number of cells to invert = light green
S and R = red
no acoustic paths = dark blue

***Figure 4.** Top subplot shows the "true" water depths as a shade plot of depth (region has also been gridded) with values as indicated by scale. The middle subplot shows the region gridded into 100m by 100m cells with the sources and arrays locations shown. The bottom subplot shows the region cells to be determined (120 of them), i.e., the light green color. Cells which contain a source or array, i.e., the red color, are considered to have already known depths (32 of them); cells outside of the SR paths (unsampled acoustically, 120 of them) will not be considered, i.e., the dark blue.*

True values



Inverted values
(rms error = 13.4 m, max error = 41.3 m)

Figure 5. Plot showing final tomographic inversion for a crudely gridded Haro Strait test where cells with 3 or fewer paths sampling them have been eliminated from the inversion (true depth values have been used in the bottom figure whenever no information was available.

RESULTS

We find a number of results:

- We *need* array information, e.g., phone sensors depths and relative ranges, in order to reduce the total number of GI unknowns and their possible values to a manageable size.

- Four frequencies seems to be a good number for convergence to a "solution", and BB is required to eliminate many non-solutions (data fits).

- NW014 and NW015 data in combination suggest that array configurations may be 3-D.

- Simulated data were very useful to provide a demonstration of the full tomographic method to estimate Haro St. water depths. While the individual SR data paths were not successfully inverted due to unknown array parameters (too large a search space otherwise), we could examine the tomographic GI as if the inversions had been done.

IMPACT/APPLICATION

This technique is likely to influence array technology, multiple array deployment, and the selection of efficient range-dependent propagation models used by the fleet for target detection, localization, and geoacoustic inversion. The estimation of true 3-D geoacoustic properties (see Tolstoy, '94; '08c) will be extremely important for the detection and localization of targets such as subs as well as of buried targets such as mines.

RELATED PROJECTS

Investigations in the area of geoacoustic inversions are being conducted by the Canadians (N. Chapman et al., Dosso et al., G. Heard et al.), Europeans (R. Hamson and M. Ainslie of Great Britain; S. Jesus of Portugal; D. Simons and M. Snellen of The Netherlands; Y. Stephan et al. of France; M. Taroudakis et al. of Greece; V. Westerlin of Sweden), and Asians (P. Ratilal et al. of Singapore; R. Zhang et al. of China). Within the US GI is being examined by D. Knobles (UT at Austin) and E. Michalopoulou at NJIT.

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HONORS/AWARDS

- Associate editor for JASA (renewed)
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